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The balance of contradictory factors in the selection of biodiesel and jet biofuels on algae fixation of flue gas

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HIGHLIGHT

- Quantitative AI model achieving uncertainty analysis and optimization of contradictory factors
- The quantitative relationship of algae products with carbon dioxide source;
- The impact of algae cultivation on the choice of jet fuel or biodiesel;
- The impact of renewable energy utilization on total energy consumption

GRAPHICAL ABSTRACT

ARTICLE INFO

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ABSTRACT

The purpose would discover the impacts of the contradictory factors in application of algae in CO2 sequestration with sustainable biofuel benefit. Based on LCA approach, the quantitively AI assessment model and approach have been established coupling upstream CO_2 source and downstream algal product at the uniform algae level of *Nannochloropsis oceanica*, which would benefit for algae biofuel deliverables choice. The AI model investigated the effects of interaction factors on the energy consumption, including transportation distances with purification modes coupling with CO_2 concentration in flue gas, lipid content with specific productivity coupling the nutrient supply, refining process with final products. Computational framework of AI model is classified into three sub-models, including CO_2 capture and purification model, algae cultivation and harvesting model, refining process and biofuel product model. According to uncertainty analysis by AI model, the positive energy gains have been conducted at a wide range of lipid contents despite of jet biofuel or biodiesel coupling solar energy utilization and by-product of bioactive nutrients effects. Biodieselwet and HTL-HRJ jet biofuel performed the priorities in energy consumption in three pathways of jet biofuel and three pathways of biodiesels. The allocation analysis confirmed that algae biofuel will be promising in the direction of cultivating appropriate algae for the target biofuel product requirement and enhancing by-product recovery. The results would enhance the interests in both LCA and CO_2 sequestration with sustainable biofuel benefit.

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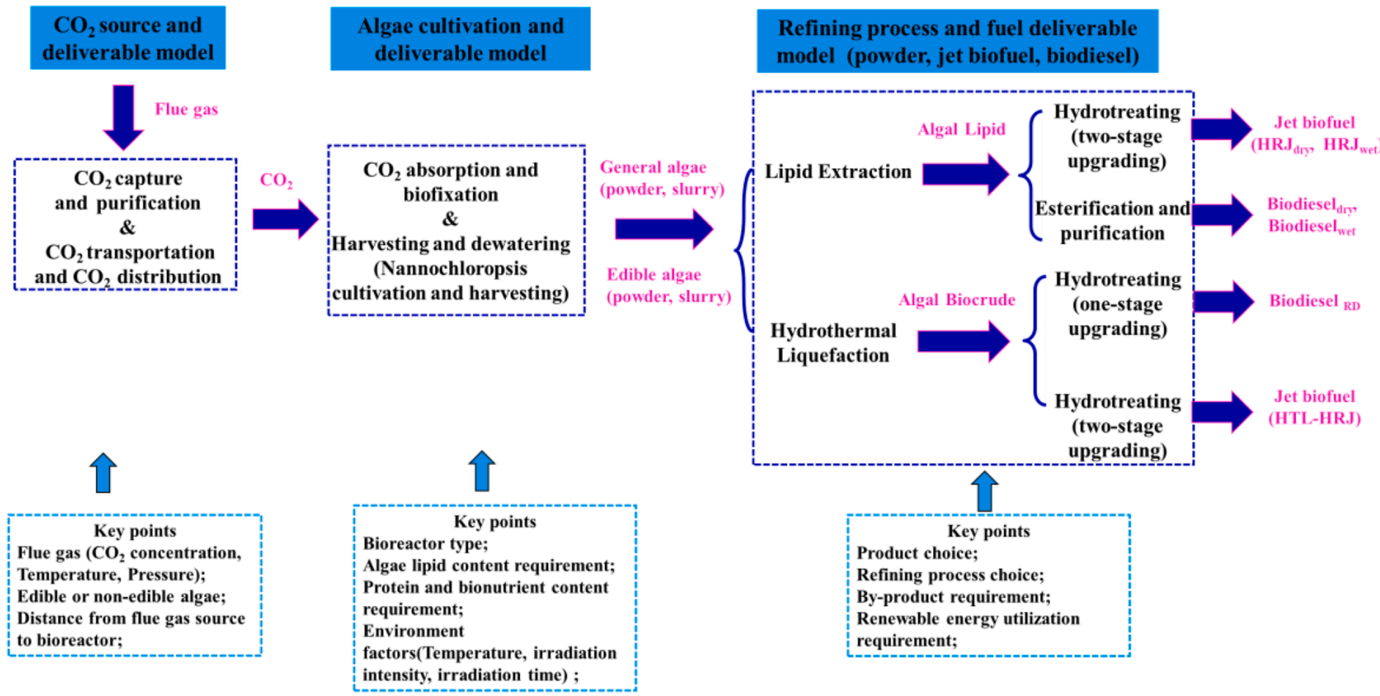


Fig. 1. System boundary and key points in every stage

1. Background

The climate change, arising mainly from flue gas emission derived from coal power industries, is a currently critical environmental issue. Considering the electricity demands and subsequent emissions, CO2 algae-fixation are becoming an attractive approach for CO2 capture and additional benefits in downstream algae utilization due to the priorities of environmental approval and sustainable potential. Flue gas derived from a coal-power station is an ideal carbon source for the large-scale culture of algae due to the stable and centralized emission features [1], which have been qualified as the carrier of bioenergy with bio-nutrient benefit in conjunction with CO2 mitigation [2,3]. However, the algae chain needs to balance economic, energy, and environmental issues in order to make targeted product selection. The improvement of flue gas purification technology of edible bio-nutrient has achieved certain economic benefits, but the energy consumption is very high. The ideal algal species should be qualified with the properties of fast growth and high content of lipids, but algae growth rate decreases obviously with the increase of lipid content. However, the increase of algae growth benefits for CO2 fixation while the increase of lipid content in algae benefits for biofuel in quality and quantity.

Most reviews [4–8] provide the most promising microalgae species for different types of biofuel. Nannochloropsis oceanica is considered as an ideal algal species characterized by rapid growth and high lipid content [9]. The challenge of the tolerance of high CO2 concentration has been overcome by gradually increasing CO2 concentration to even purified CO2 by coupling the pH control and aeration control. The pollutants in flue gas have been proved to the tolerance of SOX less than 60ppm, NO2 less than 300ppm, and NO less than 60ppm but special trace metals have been investigated aggregation in algae cells. For edible algae, flue gas must further be purified as an edible CO2 source to remove trace metals for inhibiting trace metal in bio-nutrient. Subsequently, edible CO2 requirement enhances energy consumption but benefit the economy while general algae feedstock lose advantage without edible bionutrient benefit despite enhancement in CO2 sequestration. The available algae cultivation to target appropriate algal products should also strike a balance between energy consumption and economy related to algae product in quality and quantity.

Algae industry is currently trying to achieve a broad range of products, from bio-nutrient [10–12] and animal feed [13,14] to jet biofuels [15,16] and biodiesel [17–19]. However, it is difficult to reasonably deduce the available algal final product with upstream flue gas source and appropriate algae cultivation as the complex long value chains and uncertainty in upstream algae feedstock to downstream bioenergy conversion systems. LCAs [20–25] have been undertaken aiming to assess products and processes based on available models and approaches. The current results of the assessment are complex due to the insufficient discussion of a complicated relevance system from upstream CO2 source to downstream consequences product.

In this study, quantitative assessment model has been established and can achieve uncertainty analysis and balance contradictory factors in application of algae in CO2 sequestration with sustainable biofuel benefit. Especially, mass allocation and energy allocation were involved in the model based on dimensionless values for AI assessment. The results would enhance the interests in both AI assessment of LCA and CO2 sequestration with sustainable biofuel benefit.

2. Method

2.1. Goal definition and system boundary

For balancing energy consumption of algal biofuel in quality and quantity with CO2 sequestration, the boundary of the system involved CO_2 capture and purification and algal final product. The functional units have been defined at energy consumption (MJ) per final mass product (kg) and energy consumption (MJ) per final energy yield (MJ). Accordingly, there are two flow lines to link the models. The mass flow complies with energy consumption related with final mass product (kg) while energy flow complies with energy consumption related with final energy yield (MJ).

The life cycles were classified into three stages, shown in Fig. 1. The first stage is called as CO_2 source and deliverable stage including flue gas capture and purification, and subsequently CO_2 transport as well as CO_2 distribution. Flue gas was captured and purified to remove NOx, SOx and trace metal. By transporting to algae cultivation sites, flue gas was distributed into the bioreactor. The second stage was defined as the algae cultivation and deliverables stage coupling CO_2 absorption and algal biofixation. *Nannochloropsis oceanica* were cultivated in raceway ponds or photobioreactors. The third stage was defined as refining process and fuel deliverable stage, which contains three types of products including algae powder, biodiesel, jet biofuel as well as associated by-products, given in Fig. 1.

There are two pretreatment methods to obtain biofuel precursor, lipid derived from solvent extraction and biocrude derived from hydrothermal liquification. Algal lipids or biocrude as the precursors are hydrotreated by two-stage upgrading into jet biofuel. For jet biofuel, there are three types of jet biofuel including hydrotreating lipid extracted from algae slurry into jet biofuel (HRJ_{wet}), hydrotreating lipid extracted from algae powder into jet biofuel (HRJ_{dry}), and hydrotreating hydrothermal biocrude into jet biofuel (HTL-HRJ). There are two pretreatment methods to obtain biodiesel precursors, methyl fatty acid ester derived from solvent extraction with methanol and biocrude derived from hydrothermal liquification. Methyl fatty acid esters are further purified into $Biodiesel_{dry}$ and $Biodiesel_{wet}$ while biocrude is hydrotreated by one-stage upgrading into renewable diesel ($Biodiesel_{RD}$).

2.2. Computational framework and approach

According to LCA approach, computational framework is integrated into 3 sub-models, including CO2 source and deliverable model, algae cultivation and deliverable model, refining process and fuel deliverable model. CO2 deliverable model includes CO2 capture and purification, CO2 transport, and CO2 distribution. For CO2 capture and purification, there are four methods involved in CO2 deliverable model including chemical absorption, physical adsorption, membrane separation, and cryogenic distillation. For CO2 transport, feasible transportation modes for choice include tankers and pipelines based on the distance and CO2 concentration. For CO2 distribution, raceway ponds and photobioreactors are involved with consideration of scale effects.

Algae cultivation and deliverable model includes algae growth with CO2 absorption and deliverables of algae powder and algae slurry. Biofixation reactors including raceway pond and photobioreactor are involved for CO2 absorption to cultivate Nannochloropsis. The energy consumption involved in the model is classified as direct energy consumption (the power for algae suspension, power for pumping nutrient and water provision), and indirect energy consumption (nutrient supplement). Nutrients are supplied according to the stoichiometric consumption in accordance with Nannochloropsis substance contents (carbohydrate, protein, lipid, and ash) and element contents (carbon: nitrogen: phosphorus) with compensation 5% N-nutrient loss in volatilization.

Refining process and fuel deliverable model [15] is established as an integrated computerized model for assessing refining process and biofuel deliverable. The solvent extraction pretreatment process was considered homogenization and solvent extraction as well as solvent recovery derived from algae powder or algae slurry. Hydrothermal liquification pretreatment was considered stream consumption and exchanger efficiency. Lipid or biocrude as the precursors were upgraded into jet biofuel or biodiesel. Hydrogen consumption, thermal heat and electricity consumption were involved in the hydrotreating process. The purification of methyl fatty acid ester into biodiesel was considered in Biodieseldry and Biodieselwet. The input and output of material and energy are involved in the computation framework. The materials of catalyst, hydrogen, and methanol are also involved as indirect energy consumption into the computation framework.

Allocation methods were established based on dimensionless for AI assessment. Mass allocation method complies with mass ratio (Massbiofuel/Massalgae) while energy allocation method complies with energy ratio (Energybiofuel/Energyalgae) and energy input efficiency ($Energy_{biofuel}/(Energy_{algae}$ + input energy). As a result, energy load and mass load have not only practical physical significance but also additivity and comparability. The inputs of key points, given in Fig. 1, and output of energy consumption are involved in AI model. Monte Carlo search method was used to achieve to balance contradictory factors in application of algae in CO2 sequestration with sustainable biofuel benefit. Subsequently, the reduction of energy consumption can be obtained at an available condition.

Table 1
life cycle inventory in product stage

Biofuel precursor (lipid) [42]		Biofuel precursor (biocrude) [42-46]	
Extraction lipid efficiency: homogenization 90-94 %; lipid extraction 95 % (dry); 93% (wet); Material inputs: hexane 45.4 g/kg $_{lipid}$; methanol0.15 kg/kg_{lipid}; Energy use: homogenization 0.246 kWh elec./kg $_{algae}$; lipid extraction 0.51 kWh elec. + 6.83 MJ heat /kg $_{lipid}$ Product:lipid 0.118 kg - 0.44 kg/kg_{algae} By-product: residue (fertilizer) 0.55–0.88 kg/kg_{algae}, glycerin 0.145 kg/kg_{lipid}		Energy use: Hydrothermal liquefication 0.096 kWh +2.24MJ heat/$kg_{biocrude}$. Product:Biocrude 0.177 – 0.66 kg/kg $_{algae}$ By-product: glycerin 0.145 g/g_{lipid}, nutrient with vitamin E and sterol 5% kg/kg $_{lipid}$	
Lipid to jet biofuel[47]	Lipid to biodiesel [17, 18, 48]	Biocrude to jet biofuel[15, 49, 50]	Biocrude to biodiesel[51-53]
Efficiency: 65 -74.2 % Material inputs: Hydrogen 0.050 kg/kg $_{HRJdry}$; Hydrogen 0.0504 kg/kg_{HRJwet}; Catalyst Ni/Mo/Al_2O_3 Energy use: Hydrotreating 1.7 kWh elec. /kg_{HRJ}; Product: Jet biofuel 0.062-0.248 kg/kg_{algae} By-product: Gas (Methane, Ethane, Propane, CO) Naphtha 0.015 – 0.058 kg/kg_{algae}	Efficiency: transesterification 99 wt.% lipid; Material inputs: HCl = 0.085 kg/kg $_{biodiesel}$; Energy use: transesterification = 0.09 kWh elec. + 1.7 MJ heat/kg $_{diesel}$. Product: Biodiesel 0.118 g - 0.44 g/g $_{algae}$	Efficiency: 64.5 -73.2 % Material inputs: Hydrogen 0.0719kg/$kg_{HTL-HRJ}$ Cat. Ni/Al_2O_3, Ni/Mo/Al_2O_3, Energy use: Hydrotreating (two-stage upgrading) 2.2 kWh elec. /kg jet fuel. Product: Jet biofuel 0.103-0.386 kg/kg_{algae} By-product: Naphtha 0.011 – 0.043 kg/kg_{algae} Gas (Methane, ethane, Propane, CO)	Material inputs: Hydrogen 0.063 kg/kg $_{biodiesel}$ Cat. Ni/Mo/Al_2O_3, Energy use: Hydrotreating (one-stage upgrading) = 1.5 kWh elec./$kg_{biodiesel}$. Product: Biodiesel 0.14-0.48 kg/kg_{algae} By-product: Naphtha 0.023 – 0.086 kg/kg $_{algae}$ Gas (Methane, Ethane, Propane, CO)

2.3. Inventory data

The inventory data in CO_2 source and deliverable model include purification, transportation, and distribution. Flue gases derived from coal power station consist of 10 – 20% CO2 at 1.3 kg/m^3 and N2 (77%), H2O (9–14%), O2 (2–6.5%), NO (60–1500 mg/Nm3), NO2 (2–75 mg/Nm3), SO2 (0–800 mg/Nm3), SO3 (0–32 mg /Nm3), CxHy (0.008–0.4 mg/Nm3), CO (2.5–5 mg/Nm3), particulate matter (120–800 mg/Nm3), halogen acids, and heavy metals [26,27].

For the energy consumption in capturing and purifying, chemical absorption [28–30] of flue gas can be achieved at 1.19-1.22 MJ/$kgCO_2$ with 95-98% CO_2 recovery efficiency while pressure swing adsorption [29,30] of flue gas was at 0.58-0.64 MJ/$kgCO_2$ with 85-90% recovery efficiency. Membrane Separation [29–31], excludes the other parts of the flue gas by only CO_2 through the membrane wall. Commercially available uses can be obtained with energy demands of 0.25-0.27 MJ/$kgCO_2$ with 82-88% of CO_2 recovery efficiency by polymeric gas separation membranes. Cryogenic separation [30,32] with 90-95% of CO_2 recovery efficiency by condensing at an extremely low temperature,

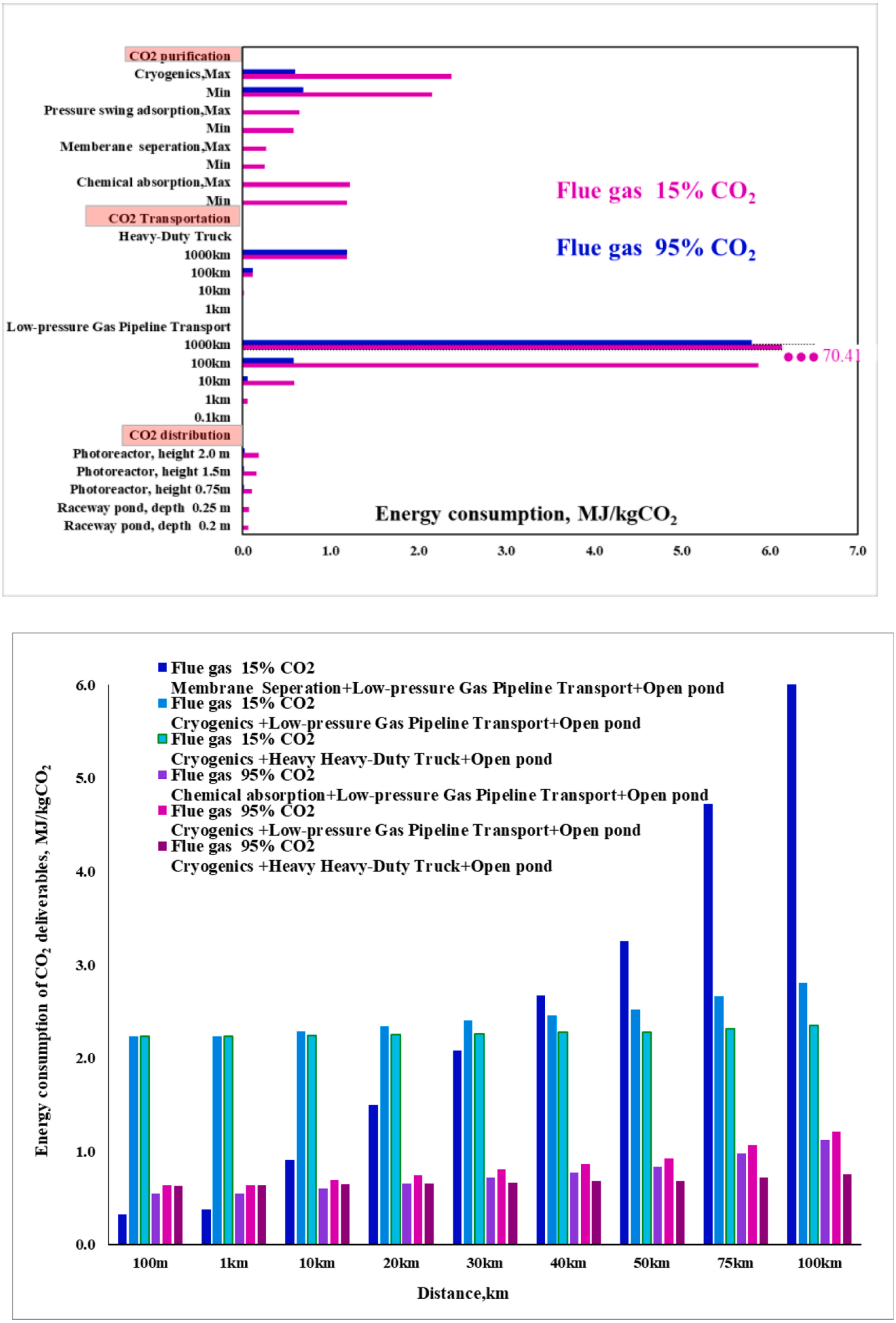


Fig. 2. Energy consumption in CO2 deliverables a. purification, transportation and distribution; b. integrating purification, transportation and distribution.The energy consumption in purification, transportation and distribution, respectively are given in Fig. 2(a) while the energy consumption integrating purification, transportation and distribution. The flue gas with low CO2 concentration performs the obvious high energy consumption in cryogenics purification process and transportation by low pressure gas pipeline, given in Fig.2 (a).

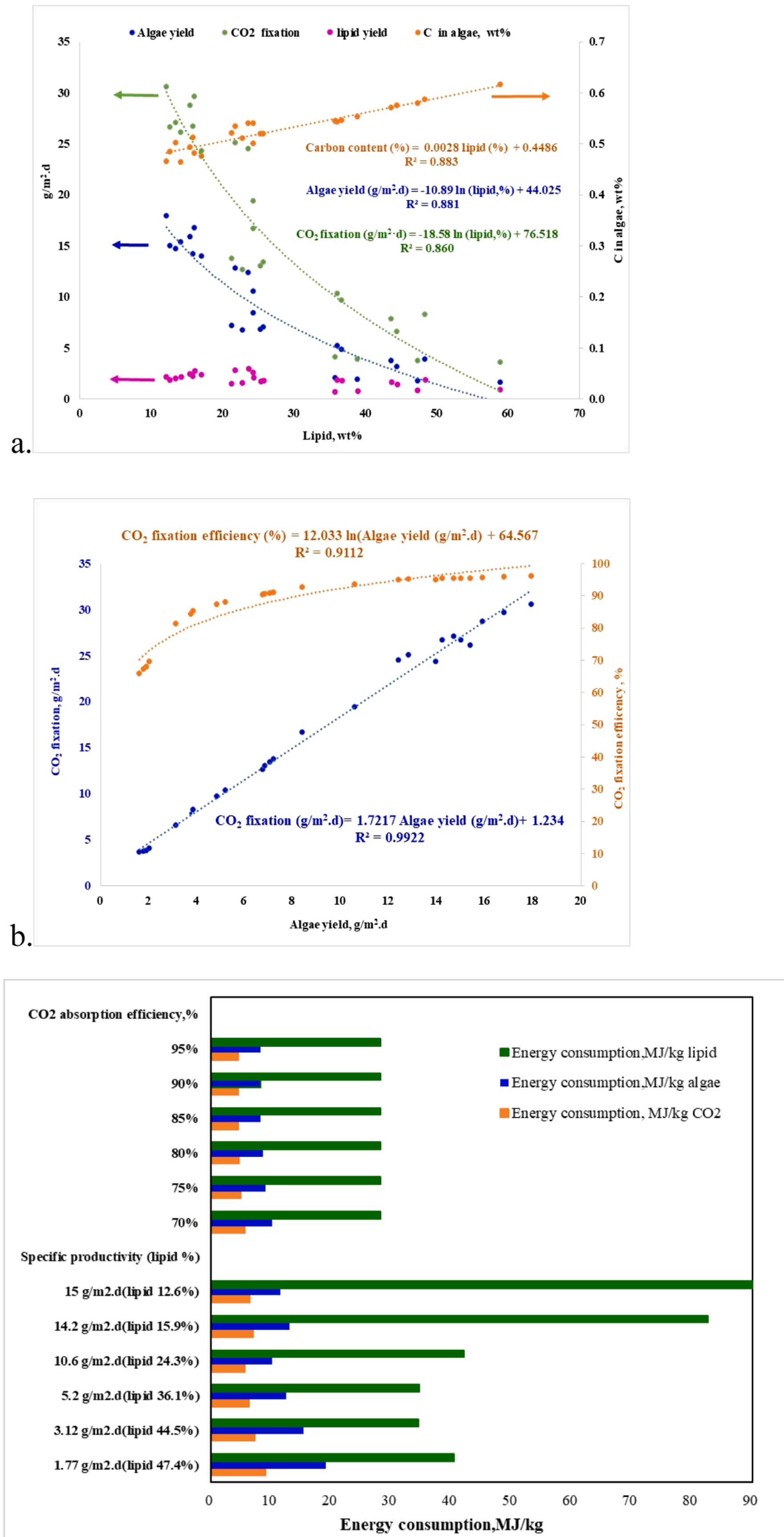


Fig. 3. Quantitative relationship related with algae deliverables a. Quantitative relationship of lipid content with algae specific productivity and CO2 fixation; b. Quantitative relationship of algae specific productivity with CO2 fixation; c. Energy consumption related with lipid content, algae productivity and CO2 fixation

excludes the other parts of the flue gas by liquified CO_2 as liquid phase. The energy consumption in low-pressure pipeline transport is collected from literature [30,32] while the energy consumption in CO_2 distribution is calculated coupling the pump efficiency and depth of the bioreactor [8].

The LCI data of *Nannochloropsis* growth were collected coupling lipid content with specific productivity by literature [2,11,12,33-36] and actual *Nannochloropsis oceanica* cultivation plant in China [1]. The influence coefficient of the external irradiation intensity, irradiation time, temperature was involved in AI model coupling CO_2 distribution and nutrient supply. Energy consumption of input materials are defined as H_2 165.5MJ/kg,Methanol 11.98MJ/kg,$(NH_4)_2HPO_4$ 17.081 MJ/kg and Urea 28.949 MJ/kg.

The LCI in refining process and biofuel deliverables, were collected based on Greet, literature, and our previous research, given in Table 1. In the lipid extraction pathway, lipid extraction was extracted by hexane extraction. The energy consumption and efficiency in the homogenization stage are 0.246 kWh elec./kg dry algae per dry metric ton with 90%. The lipid in the hexane extraction stage conforms to the lipid content in algae with extraction efficiency 95% for dry extraction and 93% for wet extraction. Algae lipid$_{dry}$ ($C_{18.18}H_{33.25}O_{3.98}N_{0.22}$) derived from dry algae and Algae lipid$_{wet}$ ($C_{18.18}H_{32.61}O_{3.76}N_{0.20}$) was hydrotreated to aviation fuel (HRJ$_{dry}$ $C_{14.81}H_{28.92}$, HRJ$_{wet}$ $C_{13.84}H_{27.3}$) based on our previous research [37] while algae lipid was transformed by transesterification into methyl fatty acid ester, namely biodiesel. In the HTL biocrude pathway, algae biocrude was obtained by hydro-liquification. The energy consumption includes the heat and pump for feedstock. Algae biocrude ($C_{15.30}H_{26.46}O_{3.44}N_{0.73}$) was hydrotreated to aviation fuel (HTL-HRJ $C_{12.64}H_{25.99}$) with 64.5% biofuel yield with 95% jet fuel based on our previous research [38,39] and to renewable biodiesel with 73 % biofuel with biodiesel 95 %.

3. Results and discussion

3.1. CO_2 source to edible and non-edible deliverables

CO2 deliverables as the upstream of algae deliverables should comply with both requirements of algae growth and transportation distance. Flue gases normally comprises CO2 in the range of 95% - 98% derived from coal chemical industries while flue gas is in the range of 12%-15%with CO, NOX, SOX, heavy metal derived from coal power stations. Considering general algae cultivation requirement, CO2 deliverables should achieve SOX≤60ppm, NO2≤300ppm, and NO ≤ 60ppm but with a wide range of CO2 concentration. Considering edible algae for bio-nutrient benefit, CO2 deliverables should achieve edible requirement with CO2 above 99.98%.

Despite flue gas concentration and energy consumption, only cryogenic fractionation can obtain liquefied pure CO2 and comply with edible algae growth requirement while the other purifications can achieve the general algae growth requirement with gas CO2. For flue gas with 15% CO2, membrane fractionation can achieve general algae growth requirement with the lowest energy consumption but cannot increase CO2 concentration obviously. Flue gas with CO2 above 95%, chemical absorption and cryogenic fractionation can be both available for general algae growth requirement.

The concentration and purity of CO2 are crucial for the choice of CO2 transportation modes. The larger volume at low CO2 concentration results in higher energy consumption in transportation distance. CO2 transportation for long distances is usually carried out in liquid phase with above 95% CO2 for a stable single-phase and less volume. The choice of appropriate mode of transportation depends on volume loads as well as transportation distance. For subsequent CO2 distribution in a bioreactor, energy consumption is related with the depth of the bioreactor, which usually are controlled at 0.25m due to photosynthetic restriction.

For flue gas with 15% CO_2, membrane separation takes the advantages in the lowest energy consumption within 30km transportation distance by pipeline. Subsequently, the main energy consumption is in the process of capture and purification with above 70% and about 20% in distribution in raceway ponds and 10% in transportation. For above 30km transportation distance, cryogenics purification with truck transportation takes obvious advantage above 40km, shown in Fig. 2 (b). For flue gas at 95% CO_2, chemical adsorption with pipeline transportation within 10km performs the lowest energy consumption while cryogenic fractionation with truck transportation at 20km performs the lowest energy consumption, shown in Fig. 2 (b). Integrating the transportation distance and purification modes, flue gas with low CO_2 concentration is appropriate for on-site utilization within 10km while flue gas with above 95% CO_2 is flexible to transportation distance and appropriate for edible CO_2 deliverable.

3.2. Algae cultivation for edible algae and algal biofuel carrier

Specific productivity and lipid content are crucial parameters related with *Nannochloropsis* deliverables in quality and quantity. Lipid content is related to bioenergy carriers and specific productivity is related to algae growth rate. For quantitively and qualitatively assessment on algae deliverable coupling the upstream CO_2 deliverable and downstream biofuel, the quantitative relationship of lipid content with specific productivity and CO_2 biofixation, are established based on lipid contents in the range of 12.6 %– 47.4 %, shown in Fig. 3(a).

The carbon content of *Nannochloropsis* is calculated based on the lipid $C_{40}H_{74}O_5$(634), protein $C_{4.43}H_7O_{1.44}N_{1.16}$(100.1), and carbohydrate $C_6H_{12}O_6$(180) content with 8% ash [45]. According to the statistics, specific productivities decrease with the increase of lipid contents in compliance with logarithmic relationship, given in equation[1]. Although carbon abundant in algae increases linearly with the rise of lipid content, given in equation [3], CO_2 fixation decreases logarithmically with the rise of lipid content, given in equation [2]. Specific productivities and CO_2 fixation both comply with negatively logarithmic relationships with lipid contents.Eqn 1, 2, 3. 4, (5)

$$Specific\ productivities(g/m^2.d) = -10.89\,ln\,(lipid\%) + 44.025 R^2 = 0.8812 \tag{1}$$

$$CO_2 fixation(g/m^2.d) = -18.58 ln(lipid\%) + 76.518 R^2 = 0.8595 \tag{2}$$

$$Carbon\ content(wt,\%) = 0.0028 lipid(\%) + 0.4486 R^2 = 0.8831 \tag{3}$$

$$CO_2 fixation(g/m^2.d) = 1.7217 specific\ productivities(g/m^2.d) + 1.234\,R^2 = 0.9922 \tag{4}$$

$$CO_2 fixation\ efficiency(\%) = 12.033\,ln(Algae\ yield(g/m^2.d) + 64.567\,R^2 = 0.9112 \tag{5}$$

According to statistics results, the lipid productivities conducted similarly at 2.25 – 2.56 g/m2.d in the wide range of specific

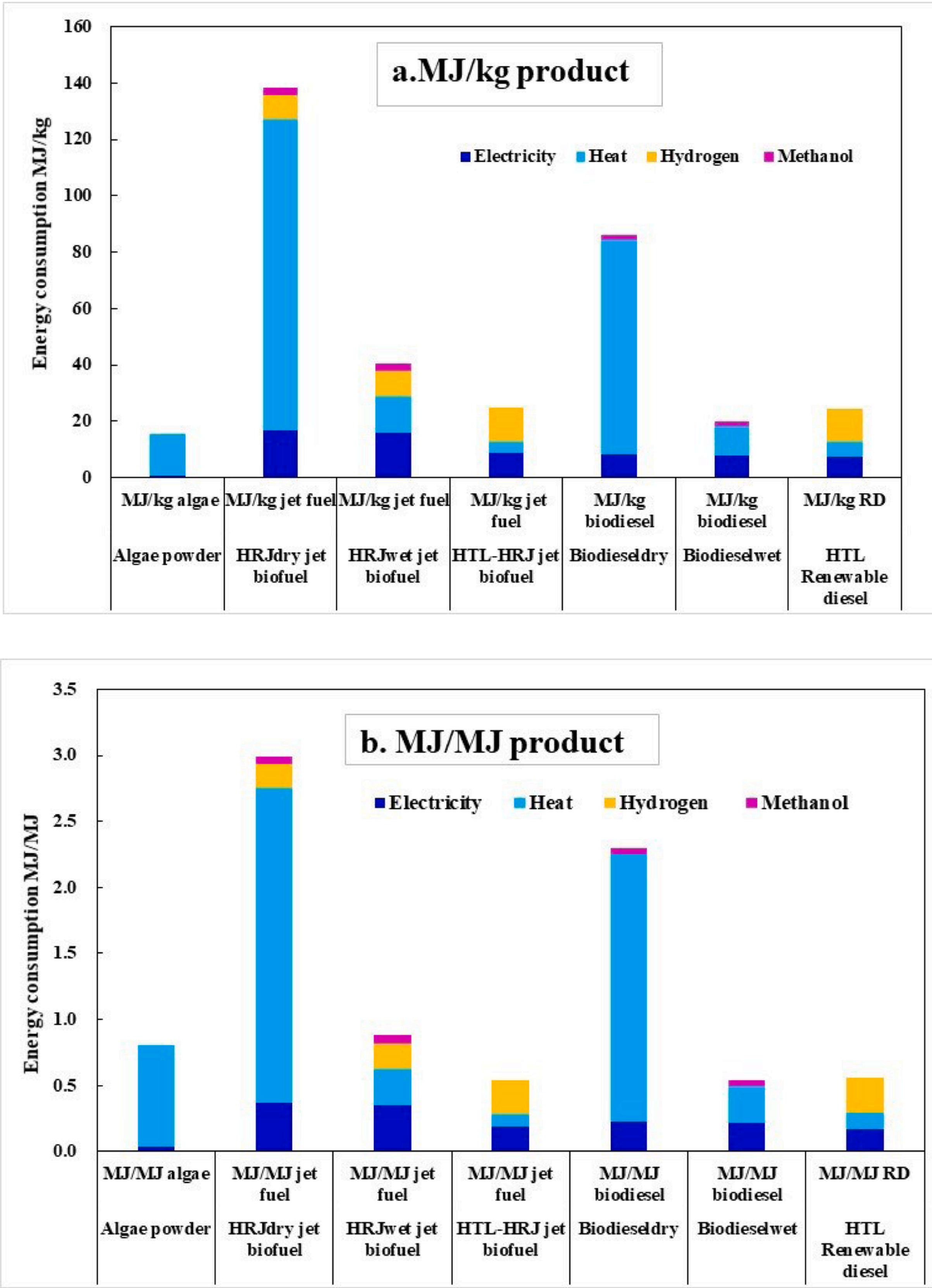
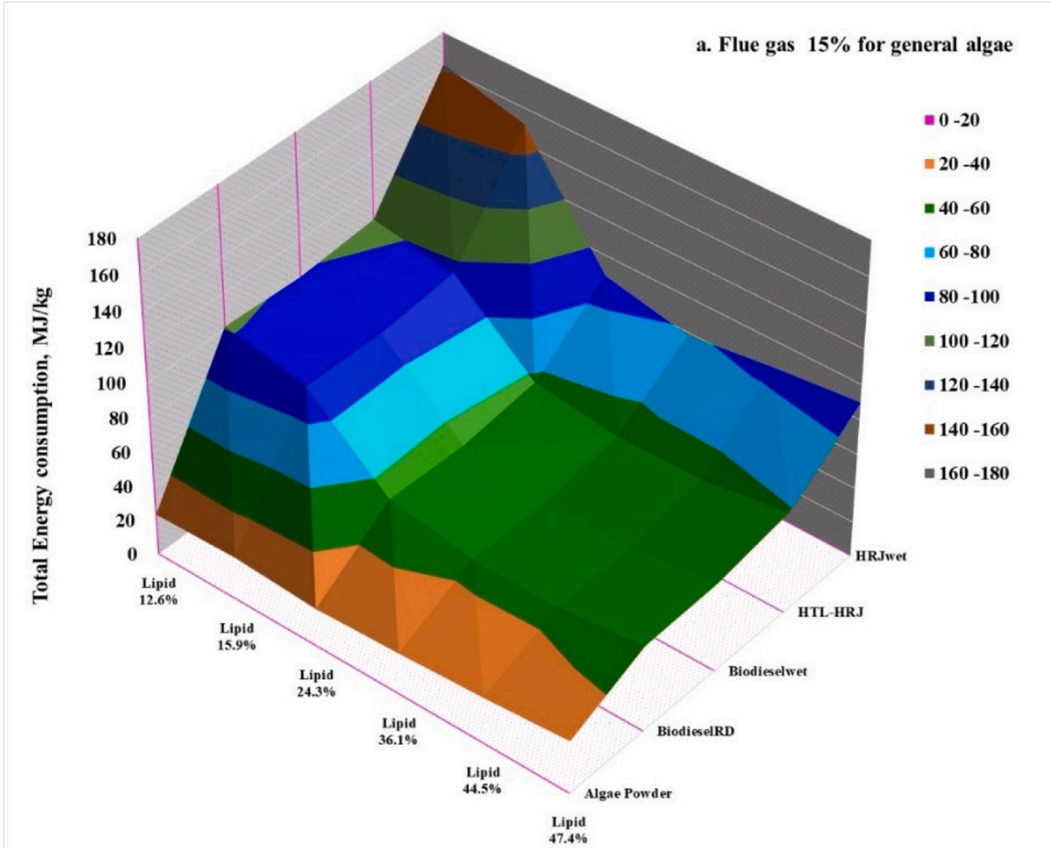


Fig. 4. Effects of refining process on energy consumption. MJ/kg product; b. MJ/MJ product. Algae powder (19.4 MJ/kg) cost energy consumption 21.7 MJ/kg and 1.12 MJ/MJ in press and dry process, which indicated that algae are unsuitable directly considering as the carrier of bioenergy due to negative energy yield. However, the thermal heat occupies around 50% in the algae powder stage, which indicates that the potential reduction of energy consumption can be improved by utilization of waste heat or solar thermal heat.



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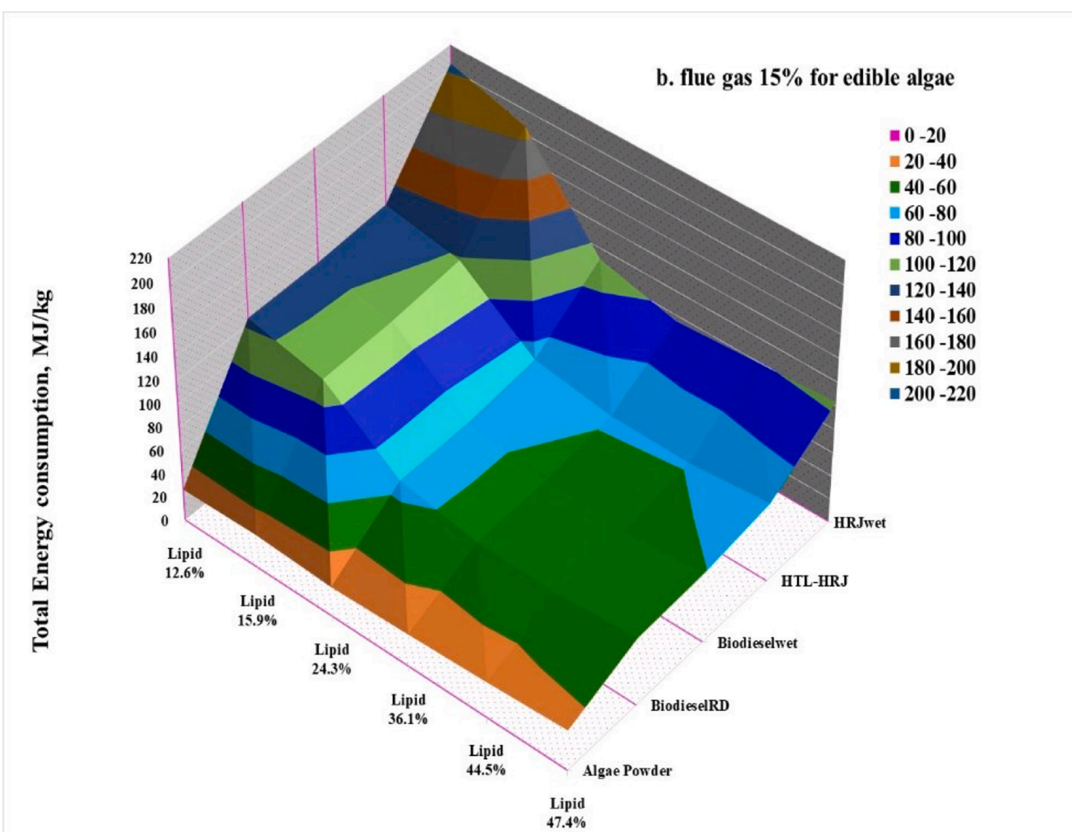
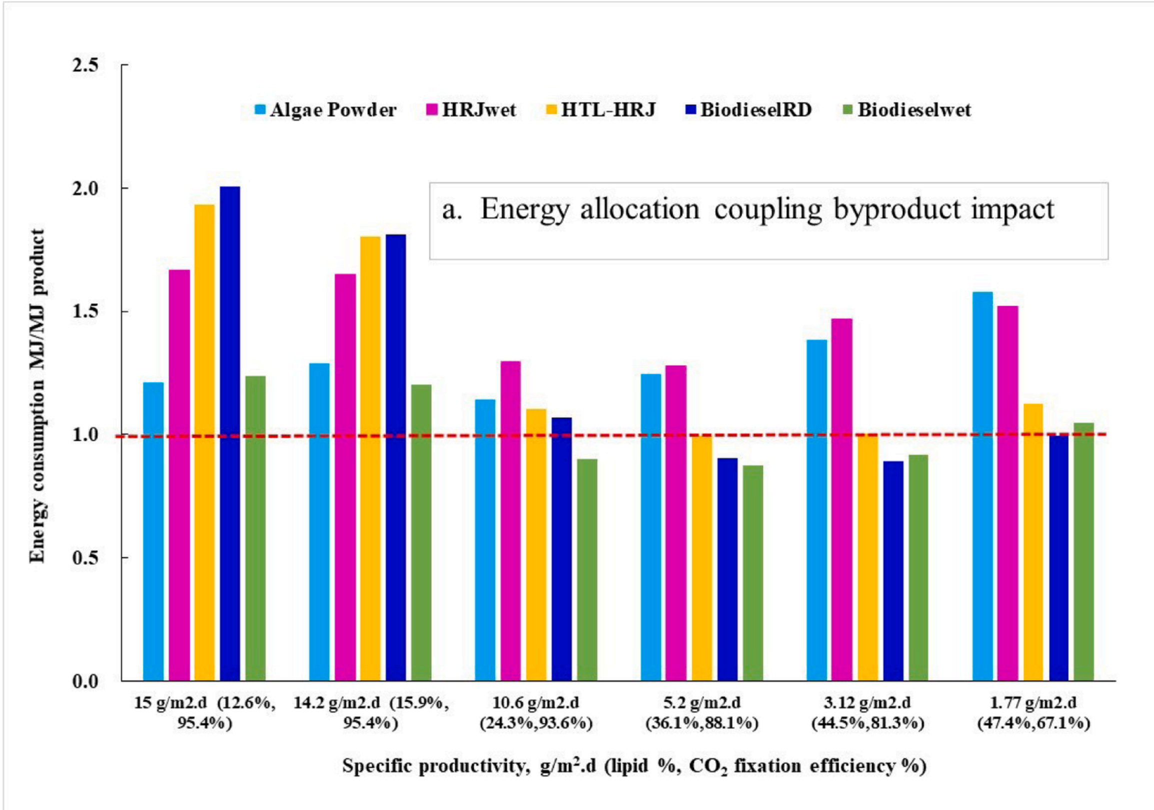


b.

Fig. 5. Total energy consumption with two types of algae for biofuel a. flue gas 15% for general algae; b. flue gas 15% for edible algae



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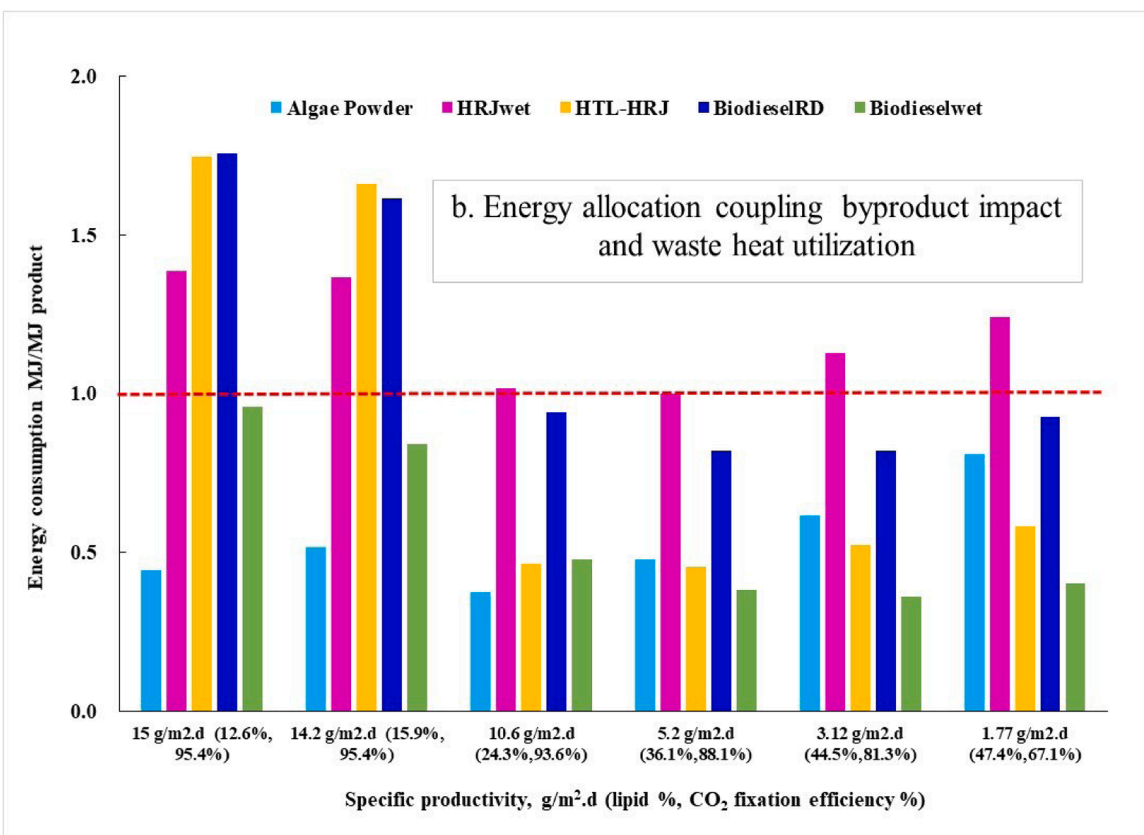

b.

Fig. 6. Total energy consumption in life cycle based on energy allocation - general algae for biofuel a. byproduct impact; b. byproduct impact and waste heat utilization

productivities and lipid contents, shown in Fig. 3(a). CO2 absorption efficiency in raceway ponds was related with algae specific productivities, shown in Fig. 3(b). CO2 fixation increases only linearly with algae specific productivities. It is investigated that CO2 evaporation loss is 1.234 g/m2.d in raceway ponds in spite of algae growth, given in equation [4]. Coupling the effects of algae specific productivity and CO2 evaporation loss, the total CO2 fixation efficiencies were investigated above 90% at below 28 % lipid content and 80- 90 % at 28% - 36% lipid content, but obviously decrease at above 40% lipid content.

Coupling the influence of specific productivity with lipid content and CO2 absorption, the lowest energy consumption per algae yield is at specific productivity 10.6 g/m2.d with lipid 24.3 % while the lowest energy consumption per algae lipid yield is at specific productivity 5.2 g/m2.d with lipid 36.1 %, shown in Fig. 3(c). Lipid content usually can be controlled by N nutrient supplement mode and algae growth cycle. The nutrient supply enhances specific productivity and protein content, but the nutrient supplement results in indirect energy consumption derived from nutrient product, which further increase the high content in carbohydrate with low lipid content. Therefore, specific productivity with lipid content could be controlled by nutrient supply for reduction of energy consumption and available feedstock for downstream biofuel.

3.3. Refining process for jet biofuel and biodiesel

Nannochloropsis (22.4 % lipid, 9.22 % protein, 60.4 % carbohydrate and 8% ash), derived from practical flue gas cultivation in China, is considered as a feedstock to evaluate the energy consumption on different biofuel deliverables by different refining process. The energy consumption based on product mass weight yield (MJ/kg product) are given in Fig. 4(a) while the energy consumption based on product energy yield (MJ/MJ product) are given in Fig. 4(b) at a uniform level of the same algae.

In three refining processes for jet biofuel, HTL-HRJ performed the lowest energy consumption, and HRJwet conducted 1.5 times and HRJdry jet biofuel conducted 5.5 times than HTL-HRJ. The energy yield of HTL-HRJ and HRJwet process can achieve positive except HRJdry process. The hydrogen utilization is the main energy consumption in HTL-HRJ processes with about 50% in total energy consumption, which indicated that fossil fuel reduction can be achieved obviously by solar energy for hydrogen in the system. The electricity utilization is the main energy consumption in HRJwet, process with around 40% while the thermal heat is the main energy consumption in HRJdry process with around 80%. The high energy consumption in HRJdry process is in the dry process for dewatering, which results in the negative energy gain.

In three pathways for algal diesel, $Biodiesel_{wet}$ process conducted the lowest energy consumption while $Biodiesel_{dry}$ conducted about 4 times and $Biodiesel_{RD}$ conducted 1.2 times. $Biodiesel_{dry}$ process performed negative energy gain as HRJ_{dry} process. $Biodiesel_{wet}$ process and $Biodiesel_{RD}$ can both achieve positive energy gain.

Coupling the refining process and biofuel product, energy yield per energy consumption in the refining fuel stage is lower than 1, which clearly implies an energy gain during the refining process. HTL-HRJ and HRJ_{wet} process perform positive energy yield for jet biofuel product while $Biodiesel_{wet}$ and $Biodiesel_{RD}$ perform positive energy yield for biodiesel product. Despite jet biofuel or biodiesel, lipids extracted by dry algae conduct the negative energy output. To compare different routes based on the energy yield despite biofuel quality and quantity, HTL-HRJ process, $biodiesel_{wet}$ and $Biodiesel_{RD}$ process conduct the priorities in energy consumption with similar positive energy gain.

3.4. Uncertainty analysis by AI model

The quality of upstream CO_2 deliverable defined the quality of downstream algae. The edible algae need cryogenic fractionation purification with benefit for bionutrient while general algae can choose chemical absorption purification with benefit for less energy consumption. The effects of algae cultivation are also complex as high lipid content is associated with lower specific productivity while lower lipid content is associated with higher specific productivity. For assessing the total impacts, the total energy consumption of different target products with upstream CO_2 deliverables and algae deliverables to downstream biofuel deliverables were calculated quantitatively on edible algae (Fig.5 a) and general algae (Fig.5 b).

Despite lipid derived from edible algae or general algae, HTL-HRJ process performed obviously lower total energy consumption than HRJ_{wet} process and HRJ_{dry}. HTL-HRJ process prefers algae feedstock at 35 - 45 % lipid content with growth rate above 3 g/m^2.d while $Biodiesel_{RD}$ and $Biodiesel_{wet}$ processes also prefer the same upstream algae cultivation as HTL-HRJ process. For algae with lipid content below 15%, the high energy consumptions were captured in all refining biofuel processes. HRJ_{wet} process conducted sensitively to algae feedstock, which performs the low energy consumption only at a small range of around 24% lipid content.

For edible algae, HTL-HRJ process still takes advantage of the total energy consumption despite mass allocation or energy allocation in comparison with HRJ_{wet} process. For only lipid use despite biodiesel or jet biofuel, all target biofuels conducted negative energy gains, and negative energy gains were also investigated in the wide range of edible algae cultivation despite allocation of by-products (bio-nutrients and glycerin).

For general algae, HTL-HRJ, $Biodiesel_{RD}$ and $Biodiesel_{wet}$ were investigated positive energy gains in the lipid range of 35 - 45 % with glycerin by-product. Mass allocation and energy allocation both achieved the reduction of the total energy consumption, but negative energy gains were also found in low lipid content and high lipid content, shown in Fig. 6.

In order to further reduce the potential energy consumption, the energy consumption is assessed by the assumption that all thermal heat of the whole life cycle was covered by solar energy or waste heat. Coupling solar energy utilization and by-product effects, the positive energy gains have been investigated at 15 - 45 % lipid content both for general algae or edible algae.

The assessment indicated that renewable energy utilization is a crucial issue to balance energy, environment and economy decisions on target product choice and by-products. Bioactive nutrients as by-product are not only beneficial in the economy but also in energy consumption. The results further indicated that the integrated algae utilization and waste heat can achieve significantly the reduction of energy consumption.

Modification should couple the upstream source and downstream consequences in the algae biofuel life cycle. The lipid profile of microalgae defined the possible biofuel quantity. For Nannochloropsis, the length of the carbon chain of fatty acids are in the range of C14 - C22 with 16 and/or 18 as the most abundant components [40,41], which indicated that Nannochloropsis contained the available bioactive nutrient and the appropriate carbon chain for jet biofuel and biodiesel. Jet fuel and diesel are both hydrocarbon molecules but with different carbon numbers distribution. Jet fuels are mainly in the range of C8 - C16 while diesels are mainly in the range of C12 - C20. Fatty acids of C16 and C18 are appropriate for biodiesel while fatty acids of C16 and C14 are appropriate for jet biofuel. Algae CO2 fixation will be promising in the direction of cultivating appropriate algae for the target biofuel deliverables and by-product recovery.

5. Conclusions

Coupling transportation distances and purification modes with flue gas concentrations, flue gas with low CO_2 concentration is appropriate for on-site utilization within 10km while flue gas with above 95% CO_2 is flexible to transportation distance and purification modes.

Specific productivities and CO_2 fixation both comply with negatively logarithmic relationships with lipid contents while lipid contents and profile defined biofuel deliverables. HTL-HRJ, $Biodiesel_{RD}$ and $Biodiesel_{wet}$ performed positive energy gains in the lipid range of 35 - 45 % of general algae with glycerin by-product. Negative energy gains performed in the wide range of edible algae cultivation despite allocation of by-products (bio-nutrients and glycerin).

Coupling solar energy utilization and by-product effects, the positive energy gains achieved at 15 - 45 % lipid content both for general algae and edible algae. Algae CO_2 fixation can be further modified in the direction of cultivating appropriate algae for available target biofuel product and connecting upstream flue gas sources by AI model.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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